An overview of tsunami deposits along the Cascadia margin

Robert Peters[1], Bruce Jaffe[1], Curt Peterson[2], Guy Gelfenbaum[3], and Harvey Kelsey[4]

[1]***U.S. Geological Survey, University of California, Santa Cruz, California, U.S.A.***
[2]***Department of Geology, Portland State University, Oregon, U.S.A.***
[3]***U.S. Geological Survey, Menlo Park, California, U.S.A.***
[4]***Department of Geology, Humboldt State University, Arcata, California, U.S.A.***

Abstract. Records of paleotsunami deposits have been compiled from more than 50 sites along the Pacific Northwest coast from northern California, U.S.A. to Vancouver Island, British Columbia, Canada. Many of these deposits record multiple tsunamis. They are best preserved in the stratigraphy of tidal or back-barrier marshes and coastal lakes. The deposits range from less than 1 cm to more than 70 cm thick. They are composed of fine to very coarse sand and some contain multiple normally graded layers representing successive waves. Many of the deposits have been associated with coseismic subsidence, suggesting that they were produced by great earthquakes along the Cascadia subduction zone. Typical inundation distances, as measured from the shoreline, are 0.5–2 km but may be greater along rivers and estuaries. Coastal barriers up to 8 m high have been overtopped. More work is needed to establish inundation distances and run-up elevations, verify numerical models, compare local site impacts, and determine recurrence intervals.

1. Introduction

The potential for great earthquakes (M8–M9) and associated tsunamis on the Cascadia Subduction Zone (CSZ) has been the focus of a large body of research over the last two decades (e.g., Atwater, 1987; Atwater *et al.*, 1995; Clague, 1997; Darienzo *et al.*, 1994; Nelson and Personius, 1996). Although similar tectonic settings are known to produce great earthquakes and tsunamis, there is no written record of great earthquakes occurring on the CSZ. Tsunamis often leave recognizable deposits in the geologic record, allowing us to extend our knowledge of past tsunamis and their relationship to great earthquakes.

We compiled a record of tsunami deposits along the Cascadia margin. Data from these deposits can aid in the assessment of tsunami hazards by helping identify areas subject to tsunami inundation and improving estimates of potential run-up and recurrence intervals.

[1]United States Geological Survey (USGS), Pacific Science Center, University of California, 1156 High St., Santa Cruz, CA 95064 (rpeters@usgs.gov; bjaffe@usgs.gov)

[2]Geology Department, Portland State University, Portland, OR 97207-0751 (Petersonc@pdx.edu)

[3]United States Geological Survey (USGS), 345 Middlefield Rd., Menlo Park, CA 94025 (ggelfenbaum@usgs.gov)

[4]Department of Geology, Humboldt State University, Arcata, CA 95521 (hmk1@axe.humboldt.edu)

2. Spatial Distribution of CSZ Tsunami Deposits

More than 50 sites containing potential or confirmed tsunami deposits have been identified along most of the Cascadia margin from northern California, U.S.A. to Vancouver Island, British Columbia, Canada (Table 1, Fig. 1). There appears to be a gap north of the Copalis River in northern Washington and small gaps in central Oregon, southern Oregon, and Northern California. These gaps do not imply tsunamis have not occurred at these locations in the past; the gaps are probably due to conditions unfavorable to the deposition, preservation, or identification of tsunami deposits.

3. Identification of CSZ Tsunami Deposits

Tsunamis often transport sand from offshore and from the beach and deposit it over coastal lowlands. In certain settings, this sand layer may be preserved and identified in the stratigraphic record. Tsunami deposits are best preserved and identified in coastal marshes and lake environments that do not normally get a large input of sand. However, it is often difficult to distinguish a tsunami deposit from sandy deposits left by other energetic processes, such as river flooding or storm surges. Tsunami deposits, however, have key characteristics that can be used to distinguish them from deposits formed by other processes.

Tsunami deposits may be distinguished from river deposits by distinct biological markers, spatial distribution, sediment characteristics, and geochemistry. Tsunami deposits contain marine or brackish water macro- and microfossils while fossils in river deposits, if present, would be fresh water varieties (Hemphill-Haley, 1995). Tsunami deposits fine landward, while river deposits generally fine seaward (Nelson *et al.*, 1996b). The composition and texture of the sand grains can be used to determine a coastal or upriver source (Peterson and Darienzo, 1996). Geochemical indicators, such as bromine enrichment, may indicate a marine source (Schlichting, 2000).

Storm surge deposits are more difficult to distinguish from tsunami deposits because, similar to tsunami deposits, they also contain marine or brackish water macro- and microfossils, have salt water chemistry, and thin and fine landward. Comparison of tsunami deposits from the Cascadia margin with deposits from recent tsunamis can help define distinguishing characteristics (Jaffe *et al.*, 1996). Multiple normally graded beds within a deposit suggest deposition by successive tsunami waves rather than a storm surge (e.g., Atwater and Hemphill-Haley, 1997; Nelson *et al.*, 1996b). The inclusion of rip-up clasts of peat and mud in the deposit further suggest deposition by a tsunami. Tsunamis may also have the potential to deposit sand farther inland or at higher elevation than storms (Dawson and Shi, 2000).

It also may be possible to distinguish a deposit left by a tsunami produced by a great earthquake on the CSZ from one left by a distant tsunami or a landslide. Carver *et al.* (1996) proposed using deposit extent and thickness to differentiate CSZ tsunamis from distant tsunamis by comparing them to deposits left by historic distant tsunamis. Witter (2001) uses the estimated

Figure 1: Map showing the locations of tsunami deposits along the Cascadia Margin. Numbers correspond to site locations in Table 1. Inset shows the regional tectonic setting.

Table 1: Tsunami deposits along the Cascadia margin.

Site #	Location	Latitude	Longitude	Depositional setting	# Tsunami deposits	Inundation distance (m)[a]	References
1	Koprino Harbor, Vancouver Island, BC	50.50	127.85	tidal marsh	2		Benson *et al.*, 1997
2	Neroutsos Inlet, Vancouver Island, BC	50.40	127.52	inlet/tidal marsh	2		Benson *et al.*, 1997
3	Power Lake, Vancouver Island, BC	50.14	127.08	lake/marsh	2		Clague *et al.*, 2000
4	Fair Harbor, Vancouver Island, BC	50.00	127.50	tidal marsh	2	600	Benson *et al.*, 1997
5	Zeballos, Vancouver Island, BC	49.98	126.85	marsh	1		Clague *et al.*, 2000; Bobrowski and Clague, 1995
6	Catala Lake, Vancouver Island, BC	49.80	127.10	lake	2+	500	Clague *et al.*, 1999
7	Louie Bay, Vancouver Island, BC	49.75	126.93	marsh	2		Clague *et al.*, 2000
8	Channel Lagoon, Vancouver Island, BC	49.58	126.68	marsh	1		Clague *et al.*, 2000
9	Deserted Lake, Vancouver Island, BC	49.46	126.50	lake	3	500	Hutchinson *et al.*, 2000
10	Kanim Lake, Vancouver Island, BC	49.40	126.34	lake	1	700	Hutchinson *et al.*, 1997
11	Port Alberni, Vancouver Island, BC	49.25	124.83	inlet/tidal marsh	3–11		Clague and Bobrowski, 1994; Clague *et al.*1994
12	Kakawis Lake, Vancouver Island, BC	49.19	125.90	lake	1	200	Clague *et al.*, 2000
13	Tofino, Vancouver Island, BC	49.15	125.92	coastal plain/tidal marsh	3		Clague and Bobrowski, 1994a; Clague and Bobrowski, 1994b
14	Ucluelet, Vancouver Island, BC	48.95	125.58	coastal plain/tidal marsh	3		Clague and Bobrowski, 1994a; Clague and Bobrowski, 1994b
15	Port Renfrew, Vancouver Island, BC	48.57	124.40	marsh	1		Clague *et al.*, 2000
16	Sooke Inlet, Vancouver Island, BC	48.37	123.69	marsh	1		Williams, 1995
17	Copalis River, WA	47.12	124.16	estuary/tidal marsh	1	2000[b]	Reinhart, 1991; Atwater, 1992
18	North Bay, Grays Harbor, WA	47.05	124.10	tidal marsh	1		Reinhart, 1991
19	Johns River, Grays Harbor, WA	46.90	123.98	estuary/tidal marsh	1	2000[b]	Reinhart, 1991; Shennan *et al.*, 1996
20	Grayland Plains, WA	46.79	124.08	back-barrier wetland	4–7		Schlichting *et al.*, 1999
21	North River, Willapa Bay, WA	46.75	123.77	estuary/tidal marsh	1	1000[b]	Reinhart, 1991
22	Smith River, Willapa Bay, WA	46.74	123.75	estuary/tidal marsh	1	1000[b]	Reinhart, 1991
22	Smith River, Willapa Bay, WA	46.74	123.75	estuary/tidal marsh	1	1000[b]	Reinhart, 1991
23	Bone River, Willapa Bay, WA	46.66	123.92	estuary/tidal marsh	1	3000[b]	Reinhart, 1991
24	Niawiakum River, Willapa Bay, WA	46.63	123.92	estuary/tidal marsh	1	3000[b]	Atwater, 1987; Atwater and Hemphill-Haley, 1997; Hemphill-Haley, 1995; Reinhart, 1991; Reinhart and Bourgeois, 1987; Reinhart and Bourgeois, 1989
25	Palix River, Willapa Bay, WA	46.60	123.91	estuary/tidal marsh	1	3000[b]	Reinhart, 1991
26	Long Beach Peninsula, WA	46.45	124.05	back-barrier wetland	4–7		Schlichting, 2000; Schlichting *et al.*, 1999
27	Young's Bay, Columbia River, OR	46.15	123.88	estuary/tidal marsh	2	10000[b]	Peterson *et al.*, 1993
28	Stanley Lake, OR	46.01	123.91	lake	2+		Peterson *et al.*, 1993
29	Neawanna Creek, OR	45.99	123.92	tidal channel/marsh	4		Peterson *et al.*, 1993; Darienzo, 1991; Darienzo *et al.*, 1994
30	Cannon Beach, OR	45.89	123.96	back-barrier wetland	4–7		Schlichting *et al.*, 1999; Peterson *et al.*, 1993
31	Rockaway Beach, OR	45.61	123.95	back-barrier wetland	4–7		Schlichting *et al.*, 1999
32	Wee Willies, Netarts Bay, OR	45.39	123.93	tidal marsh	2		Peterson *et al.*, 1993
33	Netarts Marsh, OR	45.37	123.97	tidal marsh	5		Darienzo and Peterson, 1995; Peterson *et al.*, 1993; Darienzo and Peterson, 1990; Darienzo, 1991, Shennan *et al.*, 1998
34	Nestucca Bay, OR	45.19	123.95	estuary/tidal marsh	3		Peterson *et al.*, 1993; Darienzo, 1991; Darienzo *et al.*, 1994; Darienzo and Peterson, 1995

Table 1: (continued)

Site #	Location	Latitude	Longitude	Depositional setting	# Tsunami deposits	Inundation distance (m)[a]	References
35	Neskowin, OR	45.12	123.98	back-barrier wetland	4–7		Schlichting *et al.*, 1999
36	Salmon River, OR	45.03	123.99	estuary/tidal marsh	1		Grant and McLaren, 1987
37	Silitz Bay, OR	44.89	123.99	estuary/tidal marsh	5		Peterson *et al.*, 1993; Darienzo *et al.*, 1994; Darienzo and Peterson, 1995
38	Yaquina River, OR	44.61	124.04	estuary/tidal marsh	3		Peterson *et al.*, 1993; Darienzo *et al.*, 1994; Darienzo and Peterson, 1995; Peterson and Priest, 1995
39	Beaver Creek, OR	44.52	124.07	marsh			Peterson, unpublished data
40	Alsea Bay, OR	44.42	124.02	estuary/tidal marsh	5	1500[b]	Peterson and Darienzo, 1996; Darienzo and Peterson, 1995
41	Umpqua River, OR	43.70	124.10	estuary/tidal marsh			Peterson, unpublished data
42	Coos Bay, OR	43.32	124.31	estuary/tidal marsh			Nelson and Personius, 1996; Peterson, unpublished data
43	Coquille River, OR	43.13	146.51	estuary/tidal marsh	11	8000[b]	Witter, 1999
44	Johnson Creek, OR	43.09	124.43	marsh		1000	Peterson, unpublished data
45	Bradley Lake, OR	43.07	124.43	lake	14	1100	Kelsey *et al.*, 1998a; Kelsey *et al.*, 1994; Nelson *et al.*, 1996a
46	Muddy Lake, OR	42.99	124.45	lake		1000	Peterson, unpublished data
47	New Lake, OR	42.96	124.46	lake		1000	Peterson, unpublished data
48	Sixes River, OR	42.87	124.54	estuary	3	1200[b]	Kelsey *et al.*, 1998b; Kelsey *et al.*, 1994; Kelsey *et al.*, 1993; Witter and Kelsey, 1994
49	Elk River, OR	42.79	124.52	marsh			Witter and Kelsey, 1994
50	Garrison Lake, OR	42.76	124.51	lake			Peterson, unpublished data
51	Euchre Creek, OR	42.56	124.39	marsh	2–4	500	Witter, 1999; Witter and Kelsey, 1996; Witter and Kelsey, 1994; Witter *et al.*, 2001
52	Crescent City, CA	41.73	124.15	freshwater marsh	13	500	Carver *et al.*, 1996; Garrison *et al.*, 1997
53	Lagoon Creek, CA	41.59	124.10	pond/marsh	6	1130	Abramson, 1998; Garrison *et al.*, 1997; Garrison-Laney, 1998

[a]Inundation distance is highly dependent on the depositional setting and local bathymetry. The distances reported for different sites or depositional settings may not be directly comparable.
[b]Inundation distance reflects travel by tsunami up river or estuary.

500–540 year average recurrence interval for great CSZ earthquakes (Atwater and Hemphill Haley, 1997) to suggest that at least two out of four sand layers in a 600-year interval were deposited by distant tsunamis or storm surges.

The stratigraphic position of the sand sheet may indicate its origin (Fig. 2). In coastal marsh stratigraphy, peat indicates a well-vegetated marsh soil that was subaerialy exposed, while mud with brackish marine diatoms indicates that deposition was in the intertidal zone. A sand sheet abruptly overlying peat and underlying tidal mud suggests that deposition of the sand sheet was associated with abrupt coseismic subsidence of a marsh, and implies deposition by a tsunami produced by a seismic event (e.g., Atwater, 1987; Nelson *et al.*, 1996b) (Fig. 2a). Preservation of rooted plant material beneath the sand deposit indicates sand deposition occurred soon after subsidence and further supports the link between subsidence and sand deposition (Atwater and Yamaguchi, 1991). A tsunami deposit overlying a buried marsh deposit that has not coseismically subsided may share many of the features of a tsunami deposit in a subsided marsh, but lack an overlying mud layer (Darienzo *et al.*, 1994) (Fig. 2b). Tsunami deposits in lakes usually consist of a bed of sand layered above and below by gyttja, an organic-rich lake mud (Hutchinson *et al.*, 1997, 2000; Clague *et al.*, 1999) (Fig. 2c). A layer of organic debris and/or a massive mud may overlie the sand layer. The source of the tsunami may not be evident from the lake sediments alone (Clague, 1997).

4. Characteristics of CSZ Tsunami Deposits

Tsunami deposits along the Cascadia margin exhibit a wide range of thickness, from less than a centimeter to over 70 cm (e.g., Clague and Bobrowski, 1994a). Typical ranges are from 1–30 cm. In general, they thin landward and away from channels (e.g., Atwater, 1987; Benson *et al.*, 1997). Locally, thick deposits may accumulate in depressions or in front of obstructions (Clague *et al.*, 1994), and near the terminus of narrow tidal creek sloughs (Peterson and Priest, 1995).

The grain-size distributions of CSZ tsunami deposits generally range from fine to very coarse sand. They often contain silt and occasionally contain gravel (e.g., Atwater, 1987; Benson *et al.*, 1997). The absence of gravel reported in many Cascadia tsunami deposits does not indicate that CSZ tsunamis were not able to transport large particles, just that large particles may not have been present or abundant in the sediment source. The deposits are usually massive to normally graded and may contain multiple fining upward sequences (e.g. Benson, *et al.*, 1997).

Internal structures that can be used to determine flow direction are rare in CSZ tsunami deposits. Oriented fossil plants (flopovers) found in the tsunami deposit at Niawiakum River indicate a landward-directed flow (Atwater and Hemphill-Haley, 1997). X-ray radiographs of cores may also show evidence of internal structures in tsunami deposits.

The lower contacts of CSZ tsunami deposits are sharp, may be irregular, and sometimes are erosive. Upper contacts may be sharp in marsh deposits

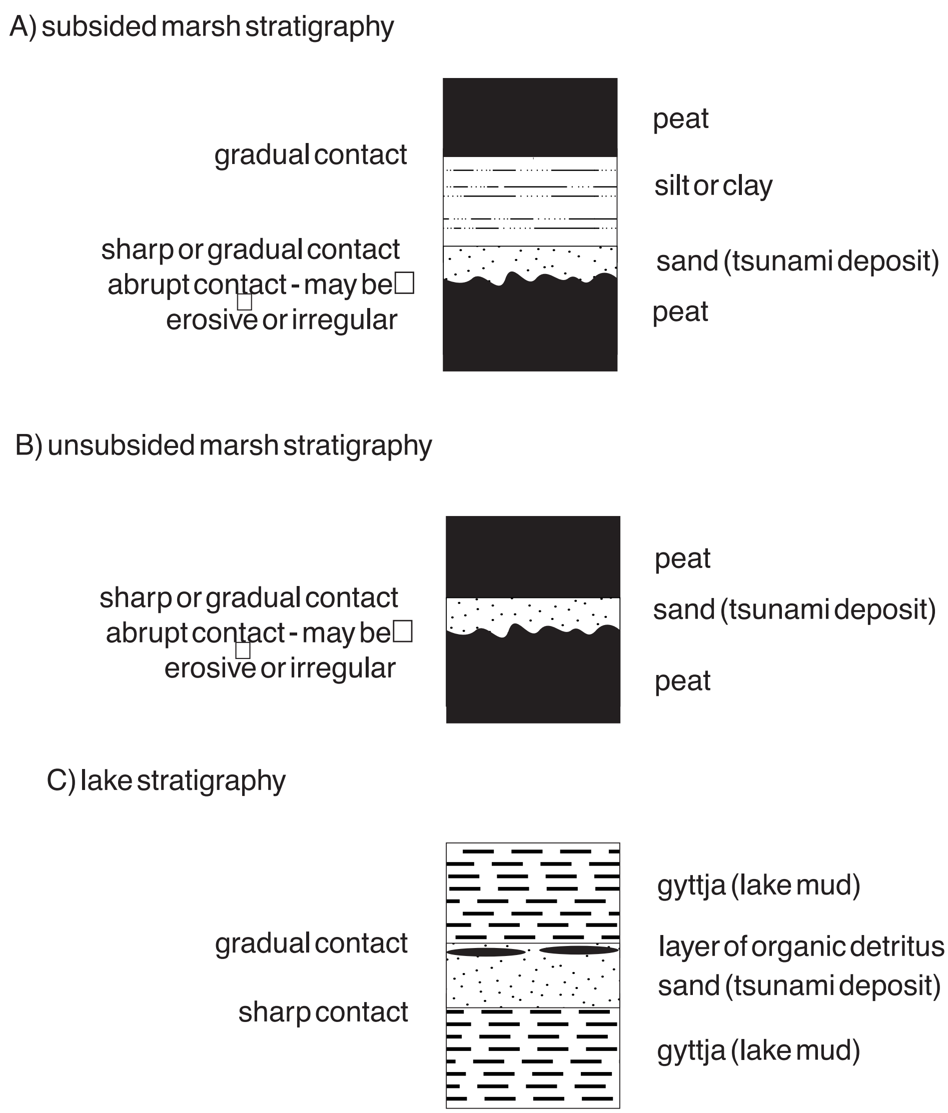

Figure 2: Typical stratigraphy of CSZ tsunami deposits. (a) A tsunami deposit within a subsided marsh stratigraphic sequence. Subsidence is indicated by a thick layer of mud above the tsunami deposit. (b) A tsunami deposit within a marsh stratigraphic sequence that has not undergone coseismic subsidence lacks an overlying bed of mud. (c) Tsunami deposits in lakes are characterized by a sandy bed layered between gyttja. A thick layer of organic debris and/or massive mud may overlie the sand layer.

(Clague *et al.*, 2000). In both lake and marsh deposits, however, the upper contact may be gradational (Hutchinson *et al.*, 1997).

CSZ tsunami deposits record inundation distances in open coastal settings (i.e., overland inundation) of greater than 1 km (Schlichting, 2000) and inundation distances may be much greater up rivers and estuaries (Table 1). Tsunami deposits at Young's Bay, on the Columbia River along the Washington/Oregon border, extend 10 km upriver (Peterson *et al.*, 1993). Tsunami deposits along the Niawiakum River reach up to 3 km inland (Atwater, 1987; Reinhart, 1991), and marine diatoms have been found up to 4 km inland (Hemphill-Haley, 1995). Typical inundation distances range from 0.5 km–2 km (Table 1).

Run-up is the maximum elevation reached by a tsunami. Minimum estimates of run-up are usually made by determining the height of barriers the tsunami had to overtop to leave the deposit. These estimates may be complicated by post-depositional elevation changes caused by tectonic, depositional, or erosional processes. Up to 8 m run-up has been inferred from tsunami deposits on Long Beach peninsula, Washington (Schlichting, 2000).

CSZ tsunami deposits have been dated using radiocarbon techniques on fossil plant material taken either from within the tsunami deposit or from directly underlying strata. This material may have been dead for some time at the time of the tsunami, so this method gives a maximum age. The most accurate dating can be achieved by sampling material that probably died during the earthquake or tsunami, such as root material in growth position. Recent tsunami deposits (such as the 1964 Alaska earthquake tsunami) may be differentiated from older tsunami deposits by elevated ^{137}Cs levels that resulted from atomic testing during the 1950s and 1960s (Benson *et al.*, 1997).

Figure 3 shows the reported age ranges of CSZ tsunami deposits. Most sites record a sand layer approximately 300 years old that probably was deposited by a tsunami that originated on the CSZ on 26 January 1700 (Satake *et al.*, 1996). Many sites also contain older tsunami deposits. The time period represented by the marsh and lake stratigraphy along the Cascadia margin ranges from several hundred years to more than 3500 years.

5. Future work

The study of tsunami deposits is still relatively new. Tsunami deposits have only been recognized along the Cascadia margin within the last 15 years, and while a large number of tsunami deposits have now been described along the Pacific Northwest coast, much work remains to be done. To assess the hazard from CSZ tsunamis, both their frequency and magnitude need to be determined. To develop an understanding of the frequency of CSZ tsunamis, we need precise and accurate dates for the tsunami deposits. Sediment transport modeling, constrained by data from tsunami deposits, can help determine size, maximum inundation, and flow velocities of CSZ tsunamis. More detailed investigations are needed where known tsunami deposits exist. Gaps in the CSZ tsunami deposit coverage should be explored for potential

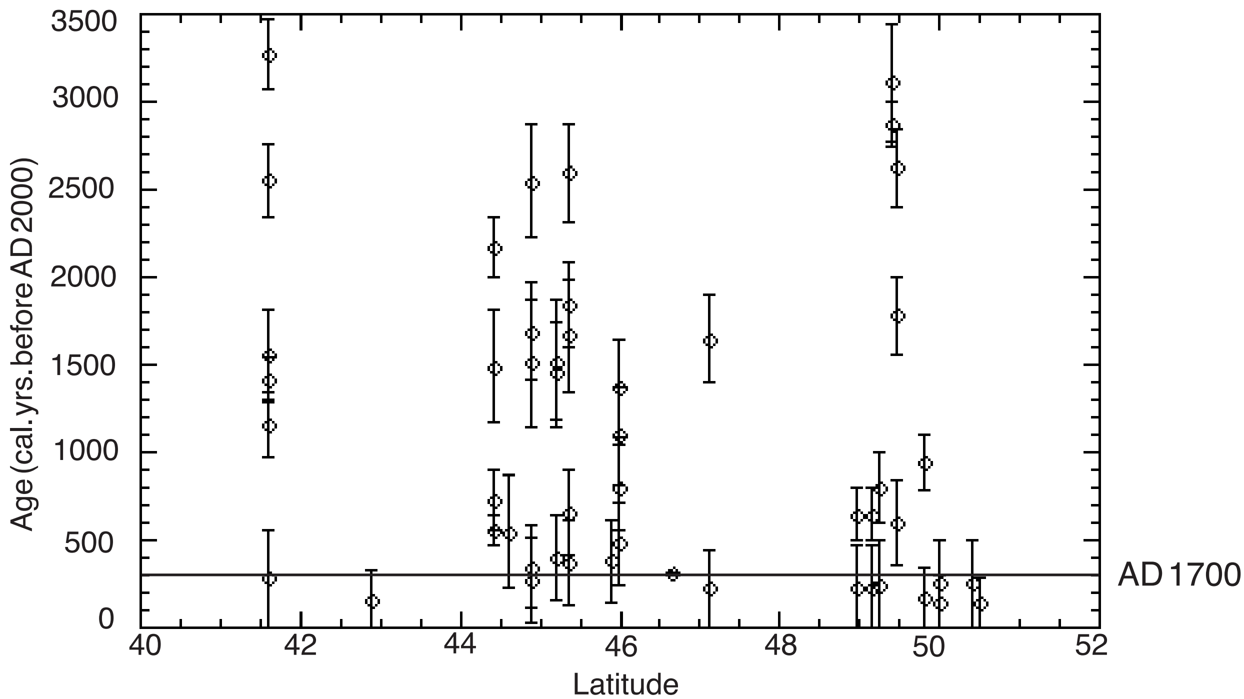

Figure 3: Reported age ranges for CSZ tsunami deposits. Ages are in calendar years before AD 2000.

tsunami deposits. We should also look beyond the borders of the CSZ for tsunami deposits that correlate with CSZ tsunamis. This will help constrain the magnitude of CSZ tsunamis and aid in determining the risk to areas both inside and outside the Cascadia margin.

6. Conclusions

Tsunamis have left recognizable deposits in coastal marshes and lakes at more than 50 sites along the entire length of the CSZ. The deposits are often associated with coastal subsidence, suggesting that many were caused by great earthquakes (M8–M9) along the CSZ. The deposits record tsunami inundation greater than 1 km in open coastal settings and up to 10 km up rivers and estuaries. Up to 8 m run-up has been inferred. A deposit associated with a tsunami that occurred approximately 300 years ago is present at most sites along the CSZ and many sites have evidence for multiple tsunamis. Further study of CSZ tsunami deposits is vital to accurately assess tsunami hazards on the Pacific Northwest coast.

Acknowledgments. We thank all of the investigators whose research is the basis for this overview. We also are grateful to Eric Geist and Hilde Schwartz for their helpful reviews. This research was funded by the Tsunami Risk Assessment project of the Coastal and Marine Geology Program, U.S. Geological Survey.

7. References

Abramson, H.F. (1998): Evidence for tsunamis and earthquakes during the last 3500 years from Lagoon Creek, a coastal freshwater marsh, northern California. MS thesis, Humboldt State University, 76 pp.

Atwater, B. (1992): Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington. *J. Geophys. Res.*, *97*(B2), 1901–1919.

Atwater, B. (1987): Evidence for great Holocene earthquakes along the outer coast of Washington state. *Science*, *236*, 942–944.

Atwater, B., and E. Hemphill-Haley (1997): Recurrence intervals for great earthquakes of the past 3500 years at northeastern Willapa Bay, Washington. *U.S. Geological Survey Professional Paper 1576*, 108 pp.

Atwater, B.F., A.R. Nelson, J.J. Clague, G.A. Carver, D.K. Yamaguchi, P.T. Bobrowski, J. Bourgeois, M.E. Darienzo, W.C. Grant, E. Hemphill-Haley, H.M. Kelsey, G.C. Jacoby, S.P. Nishenko, S.P. Palmer, C.D. Peterson, and M.A. Reinhart (1995): Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone. *Earthquake Spectra*, *11*(1), 1–18.

Atwater, B., and D.K. Yamaguchi (1991): Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington state. *Geology*, *19*, 706–709.

Benson, B.E., K.A. Grimm, and J.J. Clague (1997): Tsunami deposits beneath tidal marshes on northwestern Vancouver Island, British Columbia. *Quatern. Res.*, *48*, 192–204.

Bobrowski, P.T., and J.J. Clague (1995): Tsunami deposits beneath tidal marshes on Vancouver Island, British Columbia, Canada. In *Tsunami Deposits: Geologic Warnings of Future Inundatation*, University of Washington, 22–23 May 1994, 12.

Carver, G.A., C.D. Peterson, C.E. Garrison, and R. Koehler (1996): Paleotsunami evidence of subduction earthquakes from northern California. GSA abstracts with programs, *Geol. Soc. Am.*, *28*(5), 55.

Clague, J.J. (1997): Evidence for large earthquakes at the Cascadia subduction zone. *Rev. Geophys.*, *35*(4), 439–460.

Clague, J.J., and P.T. Bobrowski (1994a): Tsunami deposits beneath tidal marshes on Vancouver Island, British Columbia. *Bull. Geol. Soc. Am.*, *106*, 1293–1303.

Clague, J.J., and P.T. Bobrowski (1994b): Evidence for a large earthquake and tsunami 100–400 years ago on western Vancouver Island, British Columbia. *Quarten. Res.*, *41*, 176–184.

Clague, J.J., P.T. Bobrowski, and T.S. Hamilton (1994): A sand sheet deposited by tsunami at Port Alberni, British Columbia. *Estuar. Coast. Shelf Sci.*, *38*, 413–421.

Clague, J.J., P.T. Bobrowski, and I. Hutchinson (2000): A review of geological records of large tsunamis at Vancouver Island, British Columbia, and implications for hazard. *Quarten. Sci. Rev.*, *19*, 849–863.

Clague, J.J., I. Hutchinson, R.W. Mathews, and R.T. Patterson (1999): Evidence for late Holocene tsunamis at Catala Lake, British Columbia. *J. Coast. Res.*, *15*(1), 45–60.

Darienzo, M.E. (1991): Late Holocene paleoseismicity along the northern Oregon coast. Ph.D. thesis, Portland State University, 167 pp.

Darienzo, M.E., and C.D. Peterson (1995): Magnitude and frequency of subduction zone earthquakes along the northern Oregon coast in the past 3,000 years. *Oregon Geology*, *57*(1), 3–12.

Darienzo, M.E., and C.D. Peterson (1990): Episodic tectonic subsidence of late Holocene salt marshes, northern Oregon central Cascadia margin. *Tectonics*, *9*(1), 1–22.

Darienzo, M.E., C.D. Peterson, and Clough (1994): Stratigraphic evidence for great subduction-zone earthquakes at four estuaries in northern Oregon. *J. Coast. Res.*, *10*(4), 850–876.

Dawson, A.G., and S.Z. Shi (2000): Tsunami deposits. *Pure Appl. Geophys.*, *157*, 875–897.

Garrison, C.E., H.F. Abramson, and G.A. Carver (1997): Evidence for repeated tsunami inundation from two freshwater coastal marshes, Del Norte County, California. GSA abstracts with programs, *Geol. Soc. Am.*, *29*(5), 15.

Garrison-Laney, C.E. (1998): Diatom evidence for tsunami inundation from Lagoon Creek, a coastal freshwater pond, Del Norte County, California. MS thesis, Humboldt State University, 97 pp.

Grant, W.C., and D.D. McLaren (1987): Evidence for Holocene subduction earthquakes along the northern Oregon coast. *Eos Trans. AGU*, *68*, 1239.

Hemphill-Haley, E. (1995): Diatom evidence for earthquake-induced subsidence and tsunami 300 yr ago in southern coastal Washington. *Bull. Geol. Soc. Am.*, *107*(3), 367–378.

Hutchinson, I., J.C. Clague, and R.W. Mathewes (1997): Reconstructing the tsunami record on an emerging coast: a case study of Kanim Lake, Vancouver Island, British Columbia, Canada. *J. Coast. Res.*, *13*(2), 545–553.

Hutchinson, I., J.-P. Guilbault, J.J. Clague, and P.T. Bobrowsky (2000): Tsunamis and tectonic deformation at the northern Cascadia margin: a 3000 year record from Deserted Lake, Vancouver Island, British Columbia, Canada. *The Holocene*, *10*(4), 429–439.

Jaffe, B., G. Gelfenbaum, and B. Richmond (1996): Comparison of tsunami deposits from two tsunamis: The 1700 Cascadia tsunami and the 1994 Java tsunami. *Pacific Congress on Marine Science and Technology*, *38*.

Kelsey, H.M., A.R. Nelson, E. Hemphill-Haley, and R.C. Witter (1998a): Short-term and long-term changes in ocean level recorded by a coastal freshwater meromitic lake, Cascadia subduction zone, southern Oregon. GSA abstracts with programs, *Geol. Soc. Am.*, *30*(7), 162.

Kelsey, H.M., R.C. Witter, and E. Hemphill-Haley (1998b): Response of a small Oregon estuary to coseismic subsidence and postseismic uplift in the past 300 years. *Geology*, *26(3)*, 231–234.

Kelsey, H.M., R.C. Witter, A.R. Nelson, and E. Hemphill-Haley (1994): Repeated abrupt late Holocene environmental changes in south coastal Oregon: Stratigraphic evidence at Sixes River marsh and Bradley Lake. GSA abstracts with programs, *Geol. Soc. Am.*, *26*(5), 524.

Kelsey, H.M., R.C. Witter, and M. Polenz (1993): Cascadia paleoseismic record derived from late Holocene fluvial and lake sediments, Sixes River valley, Cape Blanco, south coastal Oregon. *Eos Trans. AGU*, *74*, 199.

Nelson, A.R., H.M. Kelsey, E. Hemphill-Haley, and R.C. Witter (1996a): A 7500 year record of Cascadia tsunamis in southern coastal Oregon. GSA abstracts with programs, *Geol. Soc. Am.*, *28*(5), 95.

Nelson, A.R., and S.F. Personius (1996): Great earthquake potential in Oregon and Washington—an overview of recent coastal geologic studies and their bearing on segmentation of Holocene ruptures, central Cascadia Subduction zone. In *Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest*, edited by A.M. Roger, T.J. Walsh, W.J. Kockelman, and G.R. Priest, USGS Professional Paper 1560, 91–114.

Nelson, A.R., I. Shennan, and A.J. Long (1996b): Identifying coastal subsidence in tidal wetland stratigraphic sequences at the Cascadia subduction zone of western North America. *J. Geophys. Res.*, *101*(B3), 6115–6135.

Peterson, C.D., and M.E. Darienzo (1996): Discrimination of climatic, oceanic, and tectonic mechanisms of cyclic marsh burial. In *Assessing Earthquake Hazards* *and Reducing Risk in the Pacific Northwest*, edited by A.M. Roger, T.J. Walsh, W.J. Kockelman, and G.R. Priest, USGS Professional Paper 1560, 115–146.

Peterson, C.D., M.E. Darienzo, S.F. Burns, and W.K. Burris (1993): Field trip guide to Cascadia paleoseismic evidence along the northern Oregon coast: evidence of subduction zone seismicity in the central Cascadia margin. *Oregon Geology*, *55*(5), 99–114.

Peterson, C.D., and G.R. Priest (1995): Preliminary reconnaissance survey of Cascadia paleotsunami deposits in Yaquina Bay, Oregon. *Oregon Geology*, *57*(2), 33–40.

Reinhart, M.A. (1991): Sedimentological analysis of postulated tsunami-generated deposits from Cascadia great-subduction earthquakes along southern coastal Washington. Unpublished MS project, University of Washington, 77 pp.

Reinhart, M.A., and J. Bourgeois (1987): Distribution of anomalous sand at Willapa Bay, Washington: evidence for large-scale landward-directed processes. *Eos Trans. AGU*, *68*, 1469.

Reinhart, M.A., and J. Bourgeois (1989): Tsunami favored over storm or seiche for sand deposit overlying buried Holocene peat, Willapa Bay, WA. *Eos Trans. AGU*, *70*, 1331.

Satake, K., S. Kunihiko, T. Yoshinobu, and U. Kazue (1996): Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700. *Nature*, *379*(18), 246–249.

Schlichting, R.B. (2000): Establishing the inundation distance and overtopping height of paleotsunami from the late-Holocene geologic record at open-coastal wetland sites, central Cascadia margin. MS Thesis, Portland State University, 166 pp.

Schlichting, R., C. Peterson, and D. Qualman (1999): Establishing long inundation distances of prehistoric tsunami from siliciclastic and bio-geochemical tracers in open-coast, beach plain wetlands, Central Cascadia Margin, USA. *Eos Trans. AGU*, *80*, 520–521.

Shennan, I., A.J. Long, M.M. Rutherford, F.M. Green, J.B. Innes, J.M. Lloyd, Y. Zong, and K.J. Walker (1996): Tidal marsh stratigraphy, sea-level change and large earthquakes, I: A 5000 year record in Washington, USA. *Quatern. Sci. Rev.*, *15*, 1023–1059.

Shennan, I., A.J. Long, M.M. Rutherford, J.B. Innes, F.M. Green, and K.J. Walker (1998): Tidal marsh stratigraphy, sea-level change and large earthquakes, II: Submergence events during the last 3500 years at Netarts Bay, Oregon, USA. *Quatern. Sci. Rev.*, *17*, 365–393.

Williams, H.F.L. (1995): Stratigraphic and foraminiferal evidence for earthquake-induced subsidence and attending tsunami about 300 years ago at Sooke Inlet, southern Vancouver Island, Canada. In *Tsunami Deposits: Geologic Warnings of Future Inundation*, University of Washington, 22–23 May 1994, 13.

Witter, R.C. (1999): Late Holocene paleoseismicity, tsunamis, and relative sea-level changes along the south-central Cascadia subduction zone, southern Oregon, USA. Ph.D. thesis, University of Oregon, 152 pp.

Witter, R.C., and H.M. Kelsey (1994): Abrupt late Holocene relative sea-level changes in three coastal marshes along the southern Oregon portion of the Cascadia subduction zone. *Eos Trans. AGU*, *75*, 621.

Witter, R.C., and H.M. Kelsey (1996): Repeated abrupt changes in the depositional environment of a freshwater marsh: a record of late Holocene paleoseismicity at Euchre Creek, south coastal Oregon. GSA abstracts with programs, *Geol. Soc. Am.*, *28*(5), 125.

Witter, R.C., H.M. Kelsey, and E. Hemphill-Haley (2001): Pacific storms, El Niño and tsunamis: competing mechanisms for sand deposition in a coastal marsh, Euchre Creek, Oregon. *J. Coast. Geol.*, in press.